Evaluation of sprinkler actuation times in FDS and B-RISK

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Charlie Hopkin and Michael Spearpoint, OFR Consultants from Manchester, UK, evaluate sprinkler actuation times and discuss findings included in the latest *Fire Dynamics Simulator Validation Guide*

The verification and validation process of computational models is a necessary and ongoing process. Over time, new capabilities are included into the models and new experimental data becomes available. It is therefore important to know whether the tools used can encapsulate behaviours observed in real life and one method to achieve this is to benchmark the models against experimental data.

The computational fluid dynamics (CFD) based fire modelling software Fire Dynamics Simulator (FDS)[1] is commonly used in the UK for fire and smoke modelling. However, there are less 'detailed' and computationally intensive tools available, including zone modelling software, such as B-RISK[2], which may also be able to effectively determine results for design and fire scenarios. Both the FDS Validation Guide[3] and the B-RISK software example guide[4] provide an indication of model accuracy based on available experiments by means of collections of benchmarking exercises. In certain cases, simulations have been shown to match within the bounds of experimental uncertainty, while in others there is more variation.

Previous work by Bittern[5] and Wade et al.[6] involved the undertaking of experiments on sprinkler actuation in an enclosure and comparing the experiments against simulated results from the FDS 3 and BRANZFIRE (the precursor to B-RISK) computational modelling tools. More recently, Hopkin et al.[7] have benchmarked FDS version 6.6.0 against data from the same series of experiments by Bittern. The work includes an assessment of the enclosure leakage areas, selection of radiative fraction and sprinkler head C-factor. Hopkin et al. also assesses the previous work by Bittern, in particular illustrating the importance of the decisions made by the modeller in representing fire scenarios even when simulating 'simple' experiments, where data for inputs such as the heat release rate, geometry and sprinkler characteristics are available. This article presents an evaluation of sprinkler actuation times from B-RISK version 2018.04 in comparison to the work by Bittern[5] and Wade et al.[6]. The work of Hopkin et al.[7] has been incorporated into the latest FDS Validation Guide[3], and the findings included in this article.

Experiments

The set of 22 fire experiments undertaken by Bittern[5] burned a single upholstered chair within a room-sized enclosure (Figure 1). The enclosure was located on a concrete floor and had internal dimensions of 8 m by 4 m by 2.4 m high, built from timber-framed walls and ceiling and was lined with 10mm thick gypsum plasterboard. A single 0.8 m wide by 2.1 m high door was located in one of the short walls and during the experiments it was either fully open or closed. The experiments recorded the activation time of pairs of different 3 mm diameter glass bulb residential and 5 mm diameter glass bulb standard response sprinkler heads installed flush beneath the ceiling.

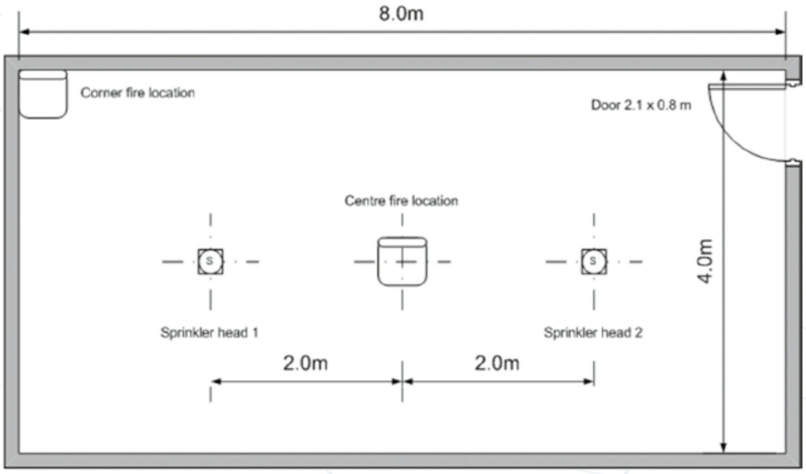

Figure 1: Enclosure layout (plan view)[5]

The upholstered chair, which is shown in Figure 2, was made of two non-fire retardant flexible polyurethane foam slabs of density 28 kg/m^3, covered with a 10 g/m^2 acrylic fabric. Each slab measured approximately 0.5 m by 0.4 m by 0.1 m thick with one forming the horizontal 'base' of the seat and the other the vertical 'back'. The slabs were placed on a metal frame and plasterboard was used to form a backing board for the seat. The chair was placed on a load cell to record mass loss with the base of the seat approximately 0.65 m from floor level. The seat was located in one of two locations in the enclosure: either in the centre or the corner opposite the door. The seat was ignited using a solid petroleum firelighter and the heat release rate (HRR) was estimated from the recorded values of mass loss rate using the heat of combustion of the foam measured in a cone calorimeter to be between 21.0 MJ/kg and 20.4 MJ/kg.

Simulations

The material and thermal properties used in Hopkin et al.[7] for the enclosure boundaries were in line with those assumed previously[5] [6] and these have been retained for the current B-RISK simulations. For the walls and ceiling plaster board these properties are thickness = 0.01 m; density = 731 kg/m^3; specific heat = 900 J/kg·K; conductivity = 0.17 W/m·K; and emissivity = 0.88. For the concrete floor the properties are thickness = 0.1 m; density = 2300 kg/m^3; specific heat = 880 J/kg·K; conductivity = 1.2 W/m·K; and emissivity (ε) = 0.50.

The simulations in Hopkin et al. and in this work use a soot yield for the polyurethane foam slabs of 0.227 kg/kg and apply the experimentally derived HRR with a burner area of 0.4 m by 0.5 m assumed for the 'base' of the seat, positioned 0.65 m from floor level. However, during the experiments, the mass loss rate was only recorded for a brief period following sprinkler actuation. The simulations are not always able to determine the time of sprinkler actuation prior to the end of the available HRR data due to overestimations in the sprinkler actuation time compared to the experiments. Therefore, some simulations have been run assuming that the fire is capped at its peak HRR and that it continues to burn at this rate until both sprinklers actuate. Figure 3 shows exemplar HRR curves used in the simulations and illustrates a single capped fire case.

The assumed sprinkler characteristics were based on the manufacturer's specification or otherwise estimated based on literature (Table 1). The offset below the ceiling has been taken to be 20 mm based on a representative sprinkler glass bulb length. One important input is the C-factor which characterises the heat loss to the sprinkler housing due to conduction. A C-factor of 0.4 $(m/s)^{1/2}$ selected for all of the sprinkler types based on sensitivity analyses undertaken in the original studies.

Figure 2: Upholstered chair in centre fire position[5]

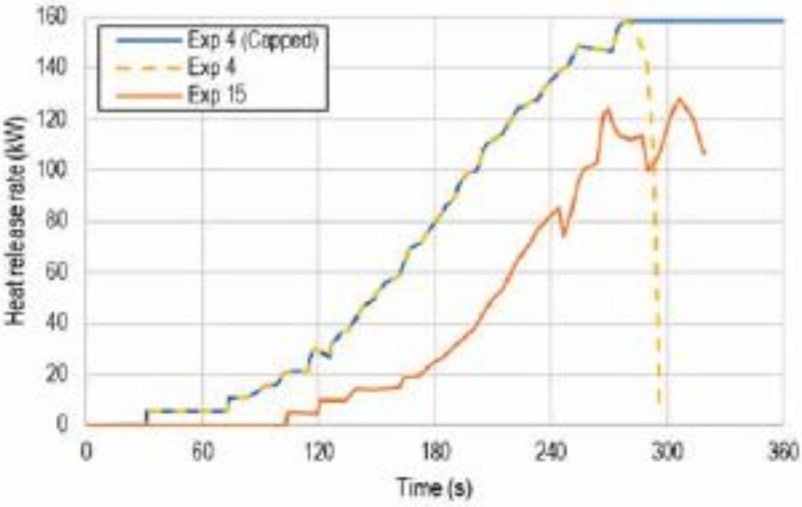

Figure 3: Example HRR curves (Experiment 4 and Experiment 15) including capped curve

The radiative fraction selected for the fire impacts on the simulations in terms of convective heat flow, which in turn affects sprinkler actuation. A radiative fraction of 0.46 has been adopted based on GM23 foam consistent with the previous work[6]. A sensitivity analysis on sprinkler activation time by Hopkin et al.[7] indicated a more consistent match with selected experimental results using this radiative fraction compared with a representative typical design value and FDS default of 0.35 for 'all other species'.

Hopkin et al.[7] included an analysis to determine an appropriate grid size in FDS which is able to best reflect the results from the experiments. Four uniform grid sizes (δx) of 0.2 m, 0.1 m, 0.05 m and 0.025 m were assessed from which a grid size of 0.05 m was found to be able to appropriately capture the sprinkler actuation times. Previously, Bittern[5]

Fire location/door configuration	Experiment	Sprinkler pair type	RTI ($m^{1/2}s^{1/2}$)	Actuation temperature (°C)	Head 1 actuation time (s)	Head 2 actuation time (s)
Fire in centre of room/door open	1	Residential	36	68	210	250
	2	Residential	36	68	225	211
	3	Residential	36	68	192	192
	4	Standard response	95	68	226	226
	5	Standard response	95	68	266	272
	6	Standard response	95	68	216	211
	7	Residential	36	68	182	186
	8	Residential	36	68	182	187
	9	Residential	36	68	233	230
	10	Residential	36	68	183	184
Fire in centre of room/door shut	11*	Standard response	95	68	199	175
	12	Standard response	95	68	246	228
	13	Standard response	95	68	204	194
	14	Standard response	95	68	203	187
	15	Standard response	95	68	270	253
Fire in corner of room/door shut	16	Residential	36	68	178	224
	17	Residential	36	68	181	228
	18	Standard response	95	68	187	221
	19	Standard response	95	68	189	223
	20	Standard response	95	68	205	None
	21	Standard response	95	93	216	330
	22	Standard response	95	93	205	263

* Excluded from analyses as mass loss rate and temperature were not successfully recorded

Table 1: Summary of experiments and sprinkler characteristics

concluded that a mesh of 0.1 m was sufficiently refined for the FDS 3 simulations, although a 0.05 m grid was shown to provide the closest match to the experiments.

For the B-RISK analyses the NIST/JET algorithm has been selected for all simulations, as this was determined in the previous BRANZFIRE study[6] to provide a closer prediction of sprinkler actuation time for the experiments than the Alpert's correlation option provided in the software. A single low-level vent of 0.053 m^2 area has been incorporated into the B-RISK simulations for experiments 12 to 22, consistent with the leakage assumed in Hopkin et al.[7].

Results and Discussion

The results of the B-RISK simulations have been compared against the results of the 2007 BRANZFIRE, where Figure 4 shows the first sprinkler head actuation time for each experiment and the estimated actuation time in BRANZFIRE and B-RISK. From this it can be observed that the modelling for B-RISK better evaluates the experiment actuation time than indicated in the previous BRANZFIRE study, which is consistent for all sprinkler heads, with an average percentage difference of −6.4 per cent from the original study to B-RISK. As B-RISK has undergone multiple updates since the 2007 edition of BRANZFIRE, it is difficult to identify specific reasons as to why this change in calculated actuation time has occurred. The method of calculating sprinkler actuation does not differ between BRANZFIRE and the B-RISK 2018.04 version, eliminating this as a possible reason for any variation. However, both the plume entrainment and vent mixing algorithms have been updated over this period which could influence the sprinkler actuation times.

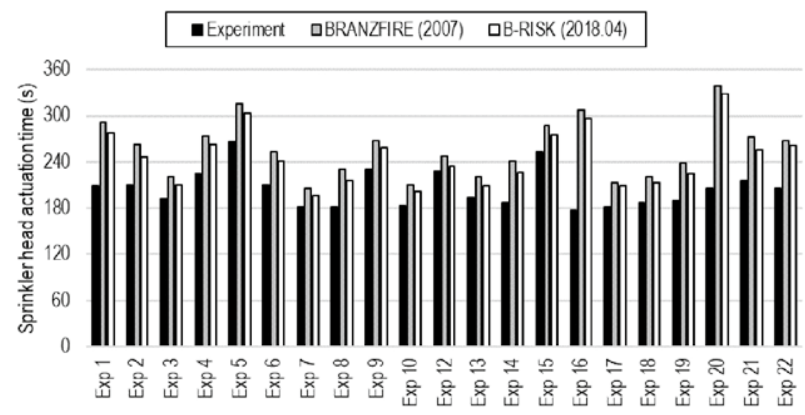

Figure 4: Comparison of results to previous study, first sprinkler head actuation time

The Euclidean Relative Difference (ERD) has been used to assess the average difference between the experimental data and the model data to provide an indication of the 'goodness of fit' beyond the visual inspection of graphs shown in Figure 4. The equation for the ERD is given by

$$\frac{||E - m||}{||E||} = \frac{\sqrt{\sum_{i=1}^{n}(E_i - m_i)^2}}{\sqrt{\sum_{i=1}^{n}E_i^2}}$$

where E is the experimental data and m is the equivalent data point estimated by the model. For this measure, the closer the model data to the experimental data, the closer the ERD is to 0[10].

Expanding on the earlier work of Hopkin et al.[7], the ERD has been calculated for all simulations using FDS and B-RISK relative to the experimental data. The ERD for all sprinkler heads and the ERD for only the first sprinkler head actuation time is shown in Table 2. The average percentage difference and the number of missing data points, i.e. non-actuated sprinkler heads within the simulations compared to the experimental data, are also shown.

Overall, the ERD indicates that the FDS simulations have better predicted the experimental results when compared to the B-RISK simulations. This is particularly true when considering the actuation of all sprinkler heads (a difference in ERD of up to 0.17). However, there is less variation between FDS and B-RISK when considering the prediction of the first sprinkler head actuation only. As shown by the average percentage difference, both B-RISK and FDS overpredict the sprinkler actuation times, with B-RISK on average predicting longer sprinkler actuation times than FDS.

In all cases it was observed visually that corner fire scenarios appeared to be less accurate for the capped fire scenarios and therefore the ERD has been calculated excluding these experiments as shown in Table 3. The accuracy of capped fire scenarios improves when excluding corner fires, as well as reducing the number of missing data points. This may indicate that, for this set of experiments, the simulations are generally better at representing fires positioned in the centre of the enclosure.

Model	All sprinkler head actuations			First sprinkler head actuation		
	ERD	Average % difference relative to experimental data	Missing data points	ERD	Average % difference relative to experimental data	Missing data points
FDS	0.11	+6.4%	6/41	0.13	+6.7%	0/21
FDS (capped fire)	0.18	+9.7%	0/41	0.15	+7.9%	0/21
B-RISK	0.18	+15.6%	14/41	0.21	+17.0%	3/21
B-RISK (capped fire)	0.35	+22.9%	0/41	0.24	+19.8%	0/21

Table 2: Euclidean Relative Difference (ERD) for sprinkler head actuations

Model	All sprinkler head actuations			First sprinkler head actuation		
	ERD	Average % difference relative to experimental data	Missing data points	ERD	Average % difference relative to experimental data	Missing data points
FDS	0.12	+6.4%	1/29	0.15	+7.3%	0/15
FDS (capped fire)	0.12	+6.5%	0/29	0.15	+7.1%	0/15
B-RISK	0.18	+14.8%	7/29	0.21	+17.5%	2/15
B-RISK (capped fire)	0.18	+15.7%	0/41	0.21	+17.4%	0/15

Table 3: Euclidean Relative Difference (ERD) for sprinkler head actuations, excluding corner fires

For B-RISK, the user is not required to consider the selection and associated sensitivity of a 'mesh', although they may consider sensitivity of other parameters. In contrast, FDS requires the user to select a mesh which can reflect experiments or designs to an 'acceptable' degree of precision. Fire engineering of buildings often requires consideration of multiple facets of design, such as the interaction between sprinklers and a ventilation system, or the impact of sprinklers with respect to tenability for means of escape and for firefighting. A fire engineer may therefore not undertake sensitivity analyses with the specific intent of determining an accurate sprinkler actuation time. In the case of FDS, they may opt to choose a coarser mesh which is able to appropriately encapsulate phenomena relevant to other aspects of design. The FDS User's Guide[1] recommends that 'in general, you should build an FDS input file using a relatively coarse mesh, and then gradually refine the mesh until you do not see appreciable differences in your results'. This is a common and practical method adopted by fire engineers when addressing grid sensitivity even though it does not guarantee convergence as the grid is refined.

Given the potential for coarser meshes used in design, Figure 5 shows the predicted first sprinkler head actuation time for experiments 1 to 10 for FDS simulations with different mesh sizes between 0.05 m and 0.2 m. The 0.025 m grid size is not shown as Hopkin et al.[7] found, when comparing for a single experiment, that the differences between a 0.025 m and 0.05 m grid size were small. It can be observed that once the mesh size is increased from 0.1 m to 0.2 m, the accuracy of the FDS simulations are equivalent to or more conservative than that shown for the B-RISK simulations.

Parameters for numerical resolution are given in the FDS Validation Guide[3] to outline the range of applicability of the validation studies.

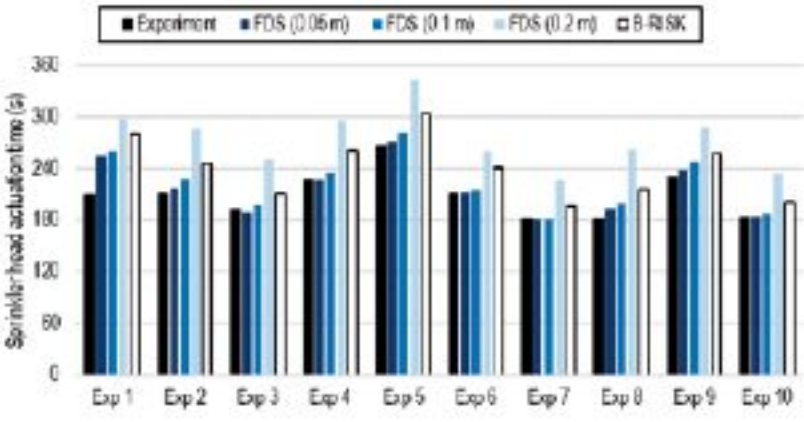

Figure 5: Mesh sensitivity comparison for Experiment 1 to Experiment 10

Grid size (m)	No. of cells	D*	H/D*	D*/δx
0.025	6,182,400	0.3 – 0.5	4.8 – 8.3	8.3 – 20.1
0.050	772,800	0.3 – 0.5	4.8 – 8.3	5.8 – 10.0
0.100	96,600	0.3 – 0.5	4.8 – 8.3	2.9 – 5.0
0.200	12,592	0.3 – 0.5	4.8 – 8.3	1.4 – 2.5

Table 4: Mesh sensitivity analysis of grid sizes

These parameters include the characteristic fire diameter (D*) using the peak HRR, the plume resolution index (D*/δx) and the enclosure ceiling height relative to the fire diameter (H/D*). The range of values for the numerical parameters for the selected grid sizes are given in Table 4. In comparison, research document NUREG-1824[8] included a series of sensitivity analyses carried out for FDS where suitable D*/δx values typically ranged from 4 (coarse) to 16 (refined). McDermott et al.[9] have indicated previously that 'D*/δx ≈ 10 has historically been considered adequate grid resolution'.

Conclusions

For the Bittern experiments, CFD-based fire modelling in FDS is a more accurate approach for determining sprinkler actuation time when compared to zone modelling using B-RISK. However, zone modelling is still able to obtain sprinkler actuation times to a reasonable level of accuracy and this study suggests that B-RISK provides a slightly improved evaluation of sprinkler activation time compared to BRANZFIRE.

In all cases it was found that the modelling over-predicted the sprinkler actuation time and, depending on whether the fire is simulated as capped, the FDS simulations provides an ERD of 0.13 to 0.15 whereas for B-RISK, the ERD was calculated as 0.21 to 0.24. The accuracy of both FDS and B-RISK simulations improved by a reduction in ERD of as much as 0.17 when the actuation of only the first sprinkler is considered.

The comparison of accuracy presented in this article applies to circumstances where the user is provided with detailed data for the fire scenarios being analysed, such as information to obtain HRRs. In the case of FDS, the analyses are performed with a refined mesh determined from a grid sensitivity study which specifically considers sprinkler actuation time. However, when FDS is considered for coarser meshes then the zone modelling software B-RISK appears to be able to determine sprinkler actuation times to an equivalent level.

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